PRODUCTION OF SUPERCONDUCTING EQUIPMENT AT IHEP

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Abstract

The report overviews the recent SC-related R&D and production activity at IHEP. The scope of the paper extends over the items to follow. Two superconducting magnetic systems of Electron Lens for the Tevatron collider were developed, manufactured and successfully brought into operation. 42 cryogenic electrical feed boxes of various types for the Large Hadron Collider were developed, produced and commissioned. Results of development of fast-cycling SC magnets for the FAIR project are discussed. Operational experience acquired with the largest in Russia cryogenic system for cooling with a superfluid helium of SC RF separator for the beam transfer line #21from the U-70 machine is presented. Test-and-trial results with HTS current leads and dipole magnet employing Bi2223 as well as racetrack coils made of second-generation HTS are reviewed.

LOW TEMPERATURE SC MAGNETS

New generation of high energy proton accelerators is based on superconducting (SC) magnets. Cooperation with international scientific accelerator centers was developed in last 15 years. In 1999 – 2000 and 2002 – 2003 two SC magnetic systems of Tevatron Electron Lens for Fermilab, USA were developed and produced. These systems were placed in the TEVATRON accelerator (Fig.1) and operated up to now.

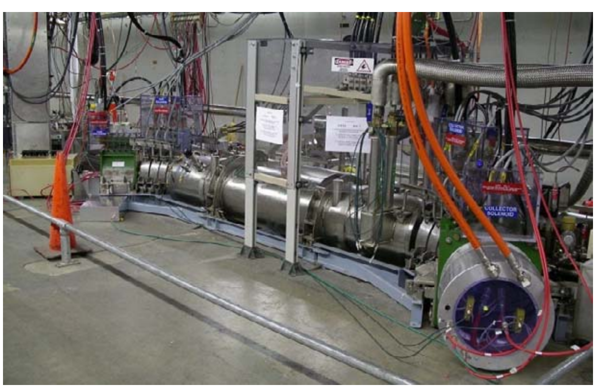

Figure 1: SC magnetic system of Tevatron Electron Lens.

The system consists of seven SC and ten copper magnets [1]. The main SC solenoid has 6.5 T nominal magnetic field, 2.5m length, 152 mm coil inner diameter. The solenoid coil was wound by the Rutherford type cable from 10 SC wires of 0.85 mm diameter. A turn number of the solenoid is 7238 and the nominal current is 1800 A. Six SC steering dipoles were placed over the solenoid. Two dipoles of 1840 mm length were arranged in the centre and four dipoles of 250 mm length in the end parts of the solenoid. The central dipole created 0.2 T magnetic field at 50 A current and the end dipole had 0.8 T at 200 A. All dipoles were wound by a cable, transposed from 8 SC wires of 0.3 mm diameter.

The system has gun and collector solenoids with 250 mm inner diameter, 474 mm outer diameter, 300 mm length, which create 0.4 T magnetic field in the aperture. Copper corrector coils are placed inside these solenoids. Three bending electron beam solenoids with 390 mm inner diameter, 500 mm outer diameter, 72 mm length are set between the cryostat and the gun solenoid as well as the same between the cryostat and the collector solenoid. A turn number of the solenoid is 48 at the nominal current 357 A. The gun, collector and bending coils of the solenoids are wound from copper cable with 8.25×8.25 mm^2 cross section having 5.5 mm diameter hole for cooling.

From 2002 IHEP collaborated with GSI, Darmstadt, Germany. SC fast cycling magnets were developed and produced for the SIS300 accelerator of the FAIR project (Facility for Ions and Antiprotons Research) [2]. The high field fast cycling dipole model is shown in Fig. 2 and its parameters are presented in Table 1.

Figure 2: SIS300 high field fast cycling dipole model.

Table 1: Parameters of the SIS300 SC fast cycling dipole

Magnetic field, T	6
Operating current, kA	6.72
Field ramp rate, T/s	1
Number of layers	2
Strand number in cable	36
AC losses (calc.), W/m	4.7
In the coil	3.4
In the iron yoke	1.3
Stored energy, kJ	260
Inductance, mH	11.7
Coil inner diameter, mm	100
Length of SC coil, m	1
Mass of magnet, ton	1.8

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A special design of SC wire and cable with stainless steel core was developed for this dipole. 6.8 T magnetic field in aperture of the dipole was reached and the magnetic field did not reduced up to 1.2 T/s ramp rate [3]. The dipole with these parameters is unique in a world practice. Fig. 3 presents the training curve and Fig. 4 shows quench currents for different ramp rates of the dipole.

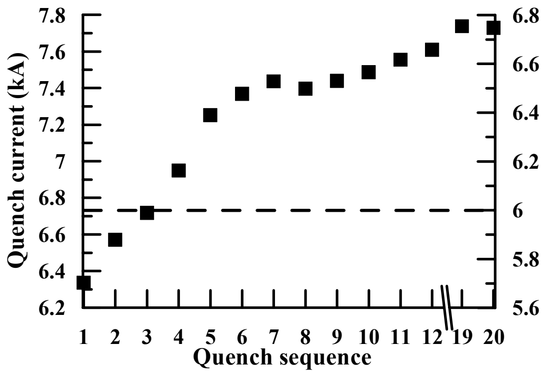

Figure 3: Training curve of the dipole.

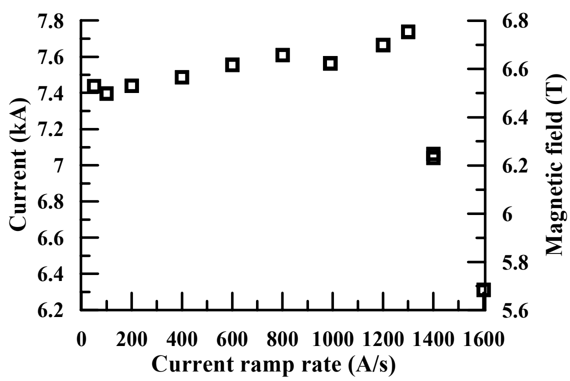

Figure 4: Ramp rate dependence of the dipole.

A prototype of the SIS300 fast cycling quadrupole was produced and tested in 2011. Design parameters of the quadrupole are 45 T/m central gradient, 10 T/m/s ramp rate, 125 mm inner diameter and 1 m effective length [4]. Fig. 5 shows a general view and Table 2 presents main parameters of the quadrupole.

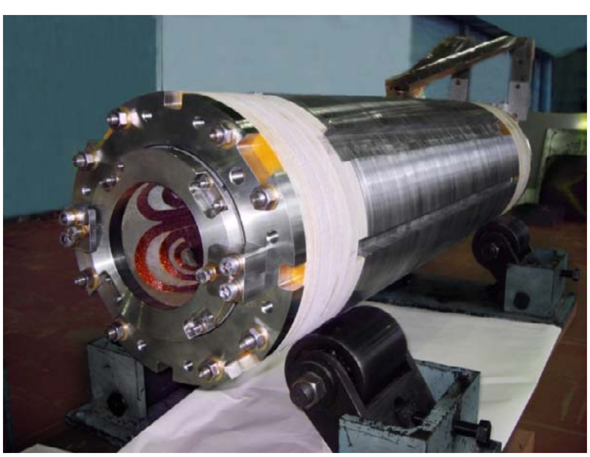

Figure 5: SIS300 fast cycling quadrupole prototype.

Table 2: Parameters of the SIS300 quadrupole prototype

Parameter	Value
Central gradient, T/m	45
Rate of central gradient, T/m/s	10
Operating current, kA	6.26
Maximum magnetic field on coil, T	3.51
Temperature margin in SIS 300 cycle, K	1.54
Stored energy, kJ	3.8
Inductance, mH	2
Number of turn in coil	80
Inner diameter of coil, mm	125
Thickness of collars, mm	22
Thickness of iron yoke, mm	52
Effective length, m	1

Fig. 6 presents training of the SIS 300 quadrupole prototype. The quench current of the magnet reached 8.2 kA in the first quench and 8.734 kA in fifth quench that corresponds to 39% current margin.

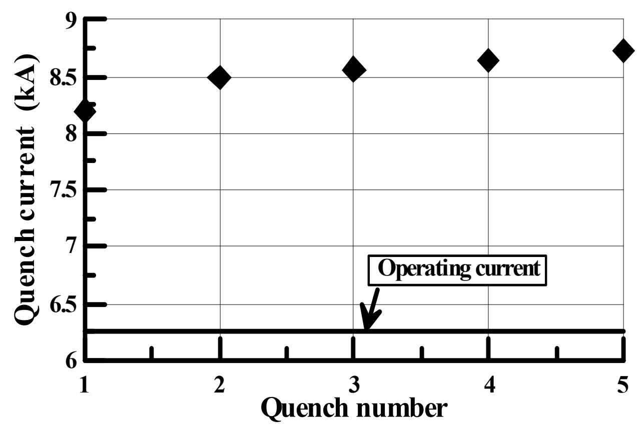

Figure 6: Quench current versus quench number of the SIS 300 quadrupole prototype.

Measurements of the quench current of the quadrupole at various ramp rates showed that the quench current was higher than 8.5 kA up to 5 kA/s (2.8 T/s) ramp rate.

Prototypes of the SIS300 fast cycling corrector magnets were developed [5]. Main requirements to these magnets are presented in Table 3.

Table 3: Requirements to SIS300 corrector magnets

Type of corrector	**Force**	***L*, m**	***t*, s**
Chromaticity sextupole	130 T/m^2	0.78	0.21
Resonance sextupole	325 T/m^2	1	0.5
Steering magnet:			
Vertical dipole	0.5 T	0.65	2.27
Horizontal dipole	0.5 T	0.65	2.27
Multipole:			
Quadrupole	1.8 T/m	0.65	2.25
Sextupole	60 T/m^2	0.65	2.18
Octupole	767 T/m^3	0.65	2.24

In the Table 3: L is the magnet length, t is a time of powering to the nominal magnetic force. The inner

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diameter of the magnets is 250 mm, the operating current is up to 250 A.

SC quadruplet of the final focus system will be used for Proton Microscope for FAIR as a large-aperture, high-gradient proton imaging lens. For strong transverse focusing, a special final focus system (FFS) has to be installed at the end of the HEDgeHOB beam line. In order to provide a focal spot of the order of 1 mm, a large focal angle is needed therefore FFS will use four large-aperture high-gradient quadrupole magnets which IHEP develops at present [6]. The quadrupole cross-section is shown in Fig. 7 and its parameters are presented in Table 4.

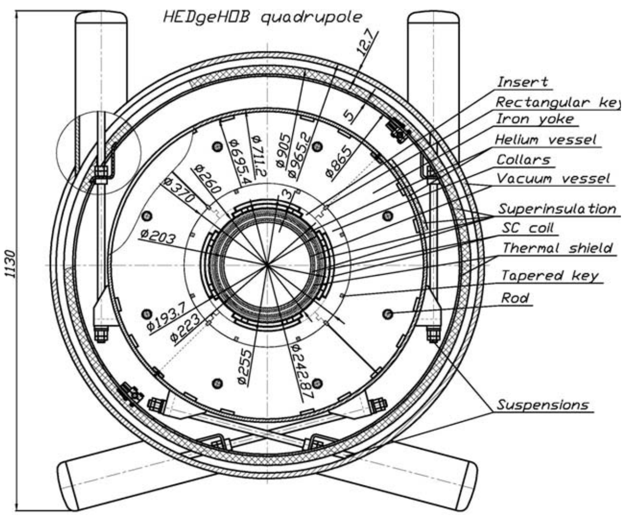

Figure 7: Cross-section of HEDgeHOB quadrupole.

Table 4: Main parameters of large-aperture high-gradient quadrupole

Central gradient, T/m	37.6
Inner diameter, mm	260
Maximal field, T	5.9
Operating current, kA	5.73
Total magnetic force/octant, kN/m	1454
Total energy in the magnet, kJ/m	613.5
Inductance, mH/m	36.5
Length of magnet, m	1.89

CRYOGENIC EQUIPMENT FOR SC SYSTEM

In frame of collaboration with DESY, Germany in 1997 IHEP produced the cryogenic helium vacuum heat exchanger for cooling 10 g/s helium flow from 300 to 2 K temperature [7], which is shown in Fig. 8.

In 2004 – 2007 years 42 Cryogenic Electrical Feed Boxes of various types for powering of SC magnets of Large Hadron Collider (Switzerland) were developed, produced and put into commission [8]. These boxes have 2600 HTS current leads with operating current from 25 to 12500 A. DFBA type box is shown in Fig. 9.

Figure 8: Cryogenic helium vacuum heat exchanger (10g/s helium flow, 300-2 K temperature range).

Figure 9: DFBA Cryogenic Electrical Feed Box for LHC.

In 2007 the largest in Russia cryogenic system for cooling SC devices by superfluid helium was put in operation at IHEP for a separated kaon beam. The system cools two SC RF cavities by superfluid helium at 1.8 K temperature [9]. The design refrigeration capacity of the cryogenic system is 280 W at 1.8 K and it should deliver 5 g/s of liquid helium per the each cavity. Main parts of the system are a satellite refrigerator and the KGU–500 cryogenic plant (Fig. 10), a cryogenic transfer line with distribution box, pumping group. The satellite refrigerator consists of a cryogenic helium vacuum heat exchanger (Fig.8), intercooling helium bath and two small helium heat exchangers, placed near each SC RF cavity. The equipment was developed and produced by IHEP. The liquid helium plant of the KGU-500 type to feed the satellite refrigerator is commercially produced by GELIYMASH company, Moscow, and it has liquefaction rate of 150 l/hr.

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Figure 10: Cryogenic plant and large helium heat exchanger of superfluid refrigerator system of 21 channel.

To reach 1.8 K the pumping group is to pump helium tanks down to 1.64 kPa. The pumping group is arranged in 3 stages: 8 Roots blowers of the 2DVN-1500 type of the first stage compress helium from 1.5 kPa to 2.5÷3.0 kPa, 8 Roots blowers of the 2DVN-500 type of the second stage compress helium to 4.0÷5.0 kPa, and the third stage of 8 slide-valve pumps of the AVZ-180 type finally compress helium up to 103 kPa.

The control system of the cryogenic system includes 240 channels of data collection and remote control, 72 electronic modules, 5 computers for inputting and outputting information in two control rooms.

Successful operation of the cryogenic system allowed one to supply necessary parameters of SC RF cavities and record more than ten millions of kaon decay events.

HIGH TEMPERATURE SC DEVICES

At the same time activity for application of high temperature superconductor (HTS) for accelerator equipment production in collaboration with Bochvar institute was begun. In 1998 – 2000 first in Russia 600 A HTS current leads on basis of Bi2223 were developed and successfully tested in the frame of contract with CERN, Switzerland [10]. The first current lead had 33 HTS tapes with Ag+10%at.Au matrix, the second one had 16 HTS tapes and the third current lead had 14 HTS tapes with Ag+1%at.Au matrix (Fig. 11).

These current leads consisted of resistive part, cooled by 20 K helium gas, and HTS part, cooled by helium vapor. The resistive part consisted of 2300 copper wires of 0.13 mm diameter, which were placed into a stainless tube of 11 mm inner diameter and 500 mm length. The HTS part was 400 mm length. The third current lead had characteristics qualified by LHC: Heat leak to liquid helium was 0.08 W at 600 A current; a resistance of joint of resistive part with HTS was 220 nΩ and that of HTS with NbTi wire was 6 nΩ; a helium flow cooled the resistive part was 0.04 g/s; a pressure drop of the helium flow was 5 kPa.

Figure 11: 600 A HTS current leads.

The next step in application of HTS is development of first in Russia HTS dipole in 2000 – 2001 [11]. The dipole has 280x345 mm^2 cross section and 590 mm length (Fig. 12). 1 T magnetic field was reached at 25 A current and 65 K temperature in 21×70 mm^2 aperture of the dipole. “Racetrack” type coil was wound by 3.8×0.25 mm^2 HTS tape which consists of Bi2223 filaments in silver matrix. The coil was placed into yoke from electric steel.

Figure 12: HTS dipole magnet.

One of the applications of new high-temperature superconductor materials (HTS) is coils for synchronous electrical machines. The use of YBCO 2G HTS tapes (HTS-2G) allows increasing of magnetic flux density in the air gap that will increase the output power and reduce the dimensions of the motor. Such motors with improved

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characteristics can be successfully used in transportation as traction motor. IHEP in collaboration with Moscow Aviation Institute designed, produced and tested HTS-2G racetrack coils for a prototype of the 50 kW synchronous motor with radial magnetic flux [12]. The HTS coils were made according to the technology of double pancake. The coil was wound on the 30 XGCA steel core (Fig. 13).

Figure 13: Four-layer racetrack coil from HTS-2G tape.

HTS coil length was 330 mm, the inner and outer diameters were 43 and 69 mm. Critical current measurements of four-layer racetrack coils from "SuperPower" HTS-2G are shown in Table 5 [13].

Table 5: Critical current of eight four-layer racetrack coils from "SuperPower" HTS-2G tapes at 77 K

Coil number	Critical current, A	
	1 μV/cm	10 μV/cm
1	38.1	41.5
2	31.4	35.4
3	34.2	38.3
4	36.3	40.3
5	31.5	35.2
6	32.8	36.4
7	34.1	37.5
8	35.9	39.6

One can see the critical current of these coils was equal to 32 – 38 A at 1 μV/cm and 35 – 41 A at 10 μV/cm. Thus, the developed production technology has allowed manufacturing these racetrack HTS coils without significant degradation of their critical current.

CONCLUSION

IHEP has meaningful experience and equipment for development and production of accelerator magnets on basis of Low Temperature Superconductors and High Temperature Superconductors as well as cryogenic system for cooling superconducting devices and systems.

At present IHEP is developing FFS superconducting large-aperture high-gradient quadrupole magnets and racetrack coils from HTS-2G tape.

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